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TITLE OF INVENTION

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Complex Polarizer System for Reciprocal Polarization (Cross-polarizer)

BACKGROUND OF THE INVENTION

The invention relates to optic systems in the visible and near-visible electromagnetic spectrum, which comprise a polarizer. More specifically, the invention relates to complex, that are compound polarizers made of several polarizing layers. The invention uncovers the principle of cross-polarization, in which complementary polarizing layers are reciprocally coupled.

DISCUSSION OF THE STATE OF THE ART

A short survey on simple polarizers (in contrast to complex, compound polarizing systems) is provided in patent application DE102004006148, the content of which is part of this application. In this publication the significance of our invention for 2-channel display systems is explained. Therefore, we present here a short overview on the state of the art of polarizing systems used in such display systems.

In 1990, Lee (DE4040081) described a layout for transmissive LCD, in which a polarizing beam splitter (PBS) was used to split an incident unmodulated light beam and a second PBS was employed to superimpose the two polarized beams after their modulation by the imagers.

For reflective polarizing systems Baur et al (US6028121) already in 1988 uncovered an architecture that includes only one PBS. This single PBS is used for both separation of the polarized beams (splitter function) and the superposition (as well as polarization recombination) of the two modulated beams. A similar polarizer arrangement is found in Gibbon et al (2001, US20030020809) and is also described in Svardal et al. in 2001 (WO03058342) for the use with LCoS (Liquid Crystal on

Silicon) Displays (Fig.1A). A somewhat similar engine, but with a split/recombination system for several color channels was described by Hattori and Oikawa in 1996 (US5798819).

For use with DMD (Digital Mirror Devices) Fielding (US20010040670) shows a light architecture with only a single PBS for beam splitting and superposition. Solutions for a 2-channel DMD system, which take into account that there is currently only one topological form of the (stereoisomer) DMD were uncovered by Bausenwein and Mayer in 2003 (DE10361915). This architecture uses two PBSs, one for beam splitting and a second for superposition.

All engines, which use a single PBS for the superposition (Fig.1A) inherit the intrinsic properties of the PBS, which are asymmetrically respective the different polarization contrast (dichroic ratio), the different intensities (transmission and reflexion are unequal) of the two beams and a geometric asymmetry in that only one beam is folded (the „S"-beam is folded by the reflexion). Simple (single) beam splitters are characterised by their different polarization contrast of the two partial beams: while the transmissive „P"-beam is „contaminated" with only 1/1000th „S"-polarized light („S"-polarized light is virtually not transmitted), the reflected „S"-beam (dotted line) contains approximately 5 percent „P"-polarized light („P"-polarized light being reflected by 5% at the PBS). Unsufficient polarization contrast is especially problematic for the use of LCoS imagers (LC-displays, which reflect bright pixels in the modulated image with a rotated polarization plane, while dark pixels are reflected without a change of polarization, Fig.1A). The „S"-beam, incident on RLM1 (spatial light modulator) contain a contamination of 5% P-polarized light (not shown). This „P"-polarized light is, at dark pixels, reflected with its incident polarization, and thus gains access to and contaminates the ON-beam of RLM1, since it has the same polarization as the modulated light reflected from bright pixels by RLM1. The transmitted „P"-light incident on RLM2 contains less polarization impurity. However, this „P"-light, reflected at dark pixels by RLM2 as „P"-light, will then partially (5%) be reflected by PBS P1 into the ON-beam of RLM2. Therefore, both channels are similarly subject to the imperfect polarization function of the PBS

(channel 1 at the incident beam when the beam is split, channel 2 at the leaving beam, when the images are superimposed), leading to a low image contrast of only about 20:1 for both channels.

As a consequence, for 2-channel display systems with LCoS displays, various architectures with complex, multiple polarizers (see Fig.1B) have been disclosed (US5921650 Doany and Rosenbluth, US6280034 Brennesholz, WO03007074 Roth and Shmuel, EP1337117 Thomson SA). The architectures of these, topologically similar solutions is shown in Fig.1B. In all cases, the polarizer is composed of 4 PBSs, the arrangement is such that the thin-film layers of the PBSs form a compound „X". Additionally, the light guidance is similar: An input PBS splits the incident beam into a reflected „S"-beam and a transmissive „P"-beam. The „S"-polarized beam, folded at P1, is then folded back parallel to the direction of incidence by P3, onto a first LCoS (RLM1) (polarization layers of P1 and P3 forming the „input quadrant" of the X-structure). The „P"-polarized beam, which transmits P1, transmits also P2 in the quadrant opposite of the input quadrant. Boths RLMs reflect the light at dark pixels (OFF) back to the light source without modulating their polarization. Bright pixels (ON) are modulated by a rotation of their polarization. The „S"-beam, wich is folded twice, will leave RLM1 as „P"-beam and leave the system straight after transmitting both P3 and P4. The „P"-beam, twice transmitting before reaching RLM2, will as „S"-beam leave the system after two reflexions at P2 and P4, together with the „P"-beam in an output quadrant of the „X"-structure, opposite to the incidence. This complex polarizer is a significant improvement relative to the single PBS solutions with LCoS displays. The advantage compared to single PBSs is provided by the combination of several polarization processes, in which the contaminations are repetitively reduced (mathematically described by a multiplication of the ratios). However, even in this arrangement of 4 PBSs there should be additional cleanup polarizers, to reduce or remove the „P"-polarized light in the „S-"light upstream and downstream of the modulators. These contaminations are a disadvange of the coupling of identical polarizations (S-S, P-P) in the two channels.

In contrast to the architecture described above we have in our application

(PCT/DE2005/000194) developed the cross-polarization, which couples complementary polarizations symmetrically and reciprocally. Three polarizing layers are arranged in a way, that both partial beams in the polarizer go both through a transmissive, and a reflective process - both beams are then of the same polarization contrast, both are of the same intensity, and both are reflected once. The cross-polarizer generates symmetric beam split or beam recombination. Moreover, complex cross-polarizers render possible very efficient architectures of systems employing two complementarily polarized light beams (e.g. 2-channel display systems with spatial light modulators).

DETAILED DESCRIPTION OF THE INVENTION

1. Working principle of the polarizers used and introduction of designators.

Polarizing layers of the beam splitter type split an unpolarized light beam in two linearly polarized light beams (Fig.2). A vector V1, coplanar with the polarization layer P1, together with the optic axis of incidence A1 and the optic axis of the reflexion A2 defines the plane of polarization (POP) of the light which is reflected from electromagnetic rays incident on the polarizing layer (polarizing reflexion) and, respectively, the plane of polarization of light which transmits the polarizing layer (polarizing transmission). Layer vector V1 and the axis of incidence A1 span the plane E1. E1 is perpendicular to the plane of polarization E2 of the transmitting beam (POPtrans). Layer vector V1 and the axis of reflexion A2 span the plane E3, which is the plane of polarization of the reflected beam (POPref).

We have introduced the terms above, because they can be used both for the thin-film polarizer (Fig 2A, e.g. MacNeille type) and for a cartesian polarizing beam splitter (Fig.2B, wire grid polarizer, e.g. Proflux™ from Moxtek).

In thin-film polarizers, which work according to Brewster´s law, the plane of incidence (POI) directly determines the plane of polarization (POP) of the transmitted and the reflected light: the transmitted light („P"-polarized) has a POP

parallel to POI (E2 in Fig.2A), the reflected light („S"-polarized) has a POP perpendicular to POI (E3 in Fig.2A). Accordingly, it is possible to determine a layer vector V in thin film polarizers (V1 in Fig.2A), which is always perpendicular to POI (in these polarizers, POP and POI are strictly coupled).

Cartesian polarizers make it possible to uncouple POP from POI (Fig.2B). The layer vector V of a cartesian polarizer is determined by properties of the polarizing layer itself (e.g. in wire grid polarizers the orientation of the wires in the polarizing layer, compare V1 of P1 in Fig.2B). Layer vectors, and accordingly the POPs, can be chosen independent from POI.

Single polarizing beam splitters of both types, thin-film and cartesian, have in common the different polarization contrast for the two partial beams. While the transmitted beam is rather clean and is contaminated with less than 1/1000, the reflected beam contains about 5% of the opposite polarization.

2. The cross-polarizer: reciprocal polarization at polarization layers, which are mutually complementary.

A central aspect of our invention is the multiple coupling of a polarizing transmission at one polarizer with a polarizing reflexion at a second polarizer, which is complementary to the former.

Three polarizing layers P1, P2 and P3 with their layer vectors V1, V2 and V3 along two optical axes A1 and A2 are structurally coupled such (Fig.3) that P1 and P2 and also P1 and P3 are mutual complementary polarizing layers. This is achieved when the plane E1 (plane in German is „*Ebene*", and we stick to the E in the translation because we do not want to confuse polarizers with planes), spanned by A1 and V1, is perpendicular to plane E2, spanned by A1 and V2, and moreover plane E3, spanned by A2 and V1, is perpendicular to plane E4, spanned by A2 and V3.

This has the functional consequence, that a polarizing transmission process along

A1 at P1 can be coupled to a polarizing reflexion process at P2 (Fig.4A) and a polarizing transmission process along A1 at P2 can be coupled with a polarizing reflexion process at P1 (Fig.4B). Moreover, a polarizing transmission process along A2 at P1 can be coupled to a polarizing reflexion process at P3, and a polarizing transmission process along A2 at P3 can be coupled to a polarizing reflexion process at P1 (not shown, comp.Fig.4).

If one choses, like in our invention, the direction of the optical axes such that these are identical to the corresponding transmission- and reflexion-axes of a possible polarization process at P1, the resulting setup can be used for our principle of reciprocal polarization (Fig.3). Mathematically described, this is achieved when the angle between the normal vector N1 of P1 and the optical axis A1 is equal to the angle between the normal vector N1 of P1 and the optical axis A2.
In our invention of reciprocal polarization at mutually complementary polarizing layers 4 polarization processes are coupled: two mutually complementary polarizations in the first optic path (transmission at P1 is coupled to reflexion at P2) are coupled to two mutually complementary polarizations in the second optic path (reflexion at P1 is coupled to transmission at P3). We call this coupling of the two couplings reciprocal polarization, because transmission and reflexion in both beams happen in opposite succession, and they happen at mutually complementary polarizers. We would like to indicate, that the described three armed cross-polarizer (Fig.3) can, by the addition of a fourth polarizing layer, be expanded to a cross-shaped layout (stippled line in Fig.3), hence the term cross-polarizer.

3. The three armed cross-polarizer (first and second embodiments of the invention)

Fig.5A shows a first embodiment of the three armed cross-polarizer, assembled with three wire grid polarizers (WGP), in which the direction of the layer vectors (grid orientation) is not specifically adjusted to the plane of incidence (POI), angles between POP and POI not equal to 0 deg or 90 deg. An unpolarized light beam incident on P1 is split into two linearly polarized light beams, both of which run through an additional polarization process, which is mutually complementary to the

first process. The beam transmitting P1 experiences a polarizing reflexion in P2, and the beam reflected at P1 experiences a polarizing transmission at P3. As has been mentioned above, it is possible with cartesian polarizers to uncouple the plane of polarization (POP) from the plane of incidence (POI). As a consequence, the POPs of the two partial beams, which are generated in the beamsplitter P1 by reflexion and transmission, have polarization planes which are NOT orthogonal towards each other (as long as V1 is neither parallel nor perpendicular to POI). As a reference system for POP (or the e-vector) of a beam we use a cartesian coordinate system xyz with the coordinates z, the direction of the beam, x, which is perpendicular to z and parallel to POI, and y which is perpendicular both to z and POI. Only after each of the beams is folded once (e.g. after the beam transmitting P1 is folded at P2 as a consequence of reflexion), both beams are, in their relative coordinate systems, „ortho-polarized" (that is the angle between their POPs is 90deg). This ortho-situation is always achieved by the cross-polarizer.

A second embodiment, as an important special case of the first embodiment, is shown in Fig.5B. Layer vectors are chosen such that V1 is perpendicular to POI and V2 and V3 are parallel to POI. Of course, the opposite angles are also feasible. This results in a cross-polarizer made of only two physical polarizing layers (one with two polarization „hotspots"). P1 now works in a rather similar way to a thin-film polarizing beam splitter (e.g. MacNeille type), if the angle of incidence is chosen as shown with 45deg to the normal of the polarzing layer. In this situation, the POP of the reflected beam is perpendicular to POI and the POP of the transmitting beam is parallel to POI. According to the state of the art for thin-film beam splitters, the beams could be designated as „S" and „P" (S=Senkrecht, german for perpendicular, and P=parallel) polarized beams.

4. Polarization contrast in the cross-polarizer

The polarization contrast resulting in a cross-polarizer is shown in Fig.6. The mutually complementary processes are quantitatively described. The usage of a cross-polarizer leads to equally high polarization contrasts for both partial beams.

The following evaluation uses data of the Proflux™ WGP from Moxtek. The linearly polarized „P" light beam transmitting P1 (transmission coefficient tc = 0.885) will be maximally reflected by P2 (reflexion coefficient rc = 0.88) (Fig.6A). The „S" polarized beam transmitts P1 minimally (tc = 0.003) and is minimally reflected by P2 (rc = 0.05) (Fig.6B). All data is taken from „Kahn: Doing it with stripes, Private Report on Projection Display, V7,No.10, 2001,http:www.profluxpolarizer.com". The mutually complementary situation is shown in Figs.6C,D. A beam incident on one of the polarizers has, in the transmitted beam a relatively high polarization contrast of 0.885/0.003 = 295:1. The reflected beam has a camparatively small contrast of 0.88/0.05 = 17.6:1. However, after the second polarization in the cross-polarizer, both beams have a equally high polarization contrast due to the coupling of a polarizing transmission and a polarizing reflexion (295 * 17.6 = 17.6 * 295 > 5000:1).

5. The 4 armed cross-polarizer (3rd and 4th embodiments of the invention)

To set up a 4 armed cross-polarizer the 3 armed cross-polarizers shown in Figs.5 are supplemented by a fourth polarization layer (Fig.7) such that P4 forms with P2 along a third optical axis A3, and with P3 along a fourth optical axis A4, an additional 3 armed cross-polarizer (comp. Fig.3). The cross-like structure of polarizing layers contains 4 quadrants, which are in the following designated as south, north, west and east quadrants. Fig.7A showns a cross-polarizer in a third embodiment of our invention where the layer vectors (and thus the resulting POPs) are uncoupled from POI.

Fig.7B shows a fourth embodiment of the disclosure, a 4 armed cross-polarizer with layer vectors parallel and perpendicular to POI. In this arrangement, it is possible to couple multiple cross-polarizers. In contrast to the third embodiment, where the cross-polarizers P1,P2,P3 (optical path is a continuous line) and P3,P4,P1 (optical path is a stippeled line) send light with a different polarization direction in the two halfs of the west quadrant, in the fourth embodiment both input cross-polarizers send „P"-polarized light into the west quadrant, and „S"-polarized light into the east

quadrant (Fig.7B). Analogous to the 3 armed cross-polarizer shown in Fig.5B, P2 and P3 have the same layer vector, additionally also P1 and P4 have the common layer vector. Therefore, the layers may have contact in the center of the arrangement or even may be realized as continuous layers. As a consequence, in this 4 armed cross-polarizer (fourth embodiment) with layer vectors parallel and perpendicular to POI it is possible to feed both P1 and P3. We have designated this arrangement the „closed" form of the 4 armed cross-polarizer, in contrast to the embodiment shown in Fig.7A, which we call the „open" form of the 4 armed cross-polarizer.

An important detail of the closed form (Fig.7B) is the central crossing line. Its physical size depends, beside imprecisions in the actual manufacturing process, also on the thickness of the cartesian polarizing layer. In the WGP made by Moxtek, it is less than 0.2μm thick. The closed form of Fig.7B (comp. also Fig.8B) illustrates the temporal commutative law for successive transmission and reflexion in the cross-polarizer: light of a certain polarization direction incident on P1 (one half of the south quadrant) will first transmit P1 and then be reflected at P2, light with the same polarization direction incident on P3 (other half of the south quadrant) will first be reflected at P3 and then transmit P1. Despite the different temporal order of these polarizing processes, both output beams sent in the two halfs of the output quadrants (east, west) are of identical intensity and of the same polarization contrast. This is caused by the multiplicative interaction of reflexion and transmission coefficients. The doubling of the incident beam width allows one to reduce the cross-polarizer footprint by a factor of 4 to only 25% of the footprint of the third embodiment (compare Figs.8A,B).

6. Cross-polarizing principle in 2-channel display systems including polarization-rotating reflective spatial light modulators (fifth and sixth embodiment)

The addition of a fourth polarizer to a 3 armed cross-polarizer has far-reaching consequences for its use. Fig.8 shows in a fifth and sixth embodiment of our disclosure the assignment of the 4 armed cross-polarizer in the open (Fig.8A) and closed (Fig.8B) form for a two-channel display system. The optical path shows a two-

channel display system with two reflective spatial light modulators (e.g. polarization rotating modulators of the type LCoS) interact with the cross-polarizer, in which the layer vectors are parallel and perpendicular to POI.

In the open form (Fig.8A) unpolarized light is incident in one half of the south quadrant (IN). „P"-polarized light, transmitting P1, is reflected at P2 and fed onto the spatial light modulator RLM1, which occupies one half of the west quadrant. „S"-polarized light, reflected at P1, transmits P3 and is fed onto RLM2, which occupies one half of the east quadrant (cross-polarizer P1,P2,P3). At dark, unmodulated light pixels (OFF) the image modulators reflect the light back, along the paths of incidence, without changing its polarization. At bright pixels (ON) the modulators will rotate the polarization of the incident beams to the complementary polarization („S"-IN becomes „P" -ON, and „P"-IN becomes „S"-ON). For the superposition of theses ON-beams into one of the halfs of the output quadrant (north) the second cross-polarizer (P4,P2,P3) is used. This open form can also be used with layer vectors different from 0deg or 90deg, therefore any polarization direction is feasable.

In the closed form (Fig.8B) it makes sense to feed both P1 and P3. Now, two three armed cross-polarizers (P1,P2,P3) and (P3,P1,P4) will split the unpolarized incident light and feed „P"-polarized into the entire west quadrant and „S"-polarized light into the entire east quadrant. While the unmodulated OFF-beams will be reflected back to the input quadrant (south), the polarization-modulated ON beams will be superponed by two further cross-polarizers (P4,P2,P3) and (P2,P1,P4) and exit the arrangement via the north quadrant. This arrangement for image modulators is such effectively shrunk. The closed form will occupy only a quarter or less than a open form. This allows one to design very compact light architectures (minimum size of the cross-polarizer is a quadratic area with a side length of RLM width).

Especially in this sixth embodiment with polarization-rotating reflective spatial light modulators the symmetrically acting principle of the cross-polarizer both for the beam split and for the superposition is very obvious. Both partial beams, derived by

the polarizing beam split, leave the cross-polarizer symmetrically into opposite directions, along the east-west axis. The same principle applies for the superposition, in which ON- and OFF- beams for both channels leave the cross-polarizer symmetrically in opposite directions along the north-south axis.

7. Cross-polarizing systems and types of polarizers used

All embodiments above are realized with wire grid polarizers, which are perpendicular to a common groundplane. The light guidance in all systems above is realized only by polarization beam splitters within the cross-polarizer. In the following we uncover that these restrictions are not necessary for the cross-polarization principle. Other arrangements and other types of polarizers are compatible with cross-polarizing systems (Fig.9).

Additional reflective means M (e.g. mirrors) in the optical path S1 between the polarizing layers of the cross-polarizer are possible (only one optical path is shown, the same applies to the second). In this case, the planes E1 and E2, defined by layers V1 and V2 and the optical axis, are not arranged on a common axis, and are thus no longer perpendicular to each other. Instead, the folded plane E1*, which is derived by E1 through successive foldings at the reflexion sites of S1 along S1, is perpendicular to E2. In Fig.9, the POI of the mirrors are chosen such that they are either parallel or perpendicular to the POPs of the folded beams. This preferred POI of the mirror is, however, not required. Other POIs may be used, however might reflect linearly polarized light as elliptically polarized light. In that case, additional polarization corrections with waveplates could be included in the systems (e.g. full wave plates). In any case, the common groundplane can be resolved by adding additional means of reflexion (compare Fig.10).

In our application DE102004006148 we have indicated that WGPs with certain layer vectors can be replaced by polarization beam splitters of the MacNeille type (e.g. P1 in Fig.9). This will be illustrated more detailled in the following embodiment.

8. The 4 armed cross-polarizer made of 4 thin-film type polarizers with polarization rotating reflective spatial light modulators (seventh embodiment of the invention)

The cross-polarizer in this embodiment (Fig.10) consists of 4 PBSs of the MacNeille type, arranged in two planes with two mirrors or total internal reflexion prisms. Input and output PBS have the same layer vectors; these two PBSs are situated directly above each other and could be made of a single physical PBS. Layer vector of polarizers P2 and P3 are perpendicular to that of P1/P4, so that the cross-polarizing principle is fulfilled. This layout has, caused by the high channel separation and very low absorption of this PBS, theoretically an even higher channel separation than a cross-polarizer made of WGPs (0.0001 polarisation impurities in the transmitting beam and 0.05 in the reflected beam, 0.95 transmission coefficient, 0.998 reflexion cooefficient, yielding a theoretical channel separation of (0.95*0.998) / (0.0001*0.05) > 180.000:1, compared to 5000:1, data taken from datasheet for PBS, Newport Oriel Instruments, Irvine, USA). Moreover, the light efficiency is enhanced from approx. 60% $(=0.885*0.88)^2$ to approx. $90\%=(0.95*0.998)^2$. As shown in Fig.8A, this open form of the 4 armed cross-polarizer can be used with polarization-rotating reflective spatial light modulators. The same layout is, of course, also possible with WGP (not shown).

9. The cross-polarizer in 2 channel display systems with image modulators of the type micro-electro-mechanical-systems (MEMS)

The distinctiveness of the light engine architecture for MEMS (Fig.11) are the characteristics of reflecting spatial light modulators, which modulate the incident light not with a change (rotation) of polarization, but with a change of the direction of the reflected light. MEMS according to the state of the art consist of an array of electronically deflectable mirrors, which reflect the ON-Beams in the direction of the normal to the modulator surface (Digital Mirror Devices, DMD by Texas Instruments). The incidence, with recent DMDs, has an angle of 24 degrees to the normal of the modulator.

DMD modulators, according to the state of the art, show stereo-isomeric characteristics (of which only one form is recently produced). Since a single polarizer folds only one partial beam at superposition, it is preferable to use either an isomeric pair of modulators or to apply an additional folding to one channel prior to superposition to obtain the virtually stereoisomeric form (Bausenwein and Mayer, DE10361915). The cross-polarizer, in contrast, folds both channels - and thus allows one to use only a single DMD type (e.g. the currently available stereoisomer) without additional means of reflexion (in Fig.11, a closed cross-polarizer is shown). The incidence on the cross-polarizer takes place under an angle of 24deg to the footprint of the arrangement. This corresponds to the double deflection angle of the micromirrors of the recent DMD. The mirrors reflect the light at bright pixels into the normal of the DMD surface. These ON-beams are superposed in a plane which is parallel to the ground plane of the cross-polarizer. Light at dark pixels will be reflected under an angle of 48 to the normal (twice the incidence angle) opposite to the incident light towards a light dump (not shown). Incidence (IN) and the output of the system (ON) in this embodiment take place in the south quadrant. In an open form according to Fig.5 a 3 armed cross-polarizer is sufficient for the system. If there are additional quarterwave-plates ($\lambda/4$) between cross-polarizer and modulators, the ON light will be guided to the north quadrant (not shown).

10. The 2 armed form of the cross-polarizer (nineth embodiment of the invention)

The 3 armed cross-polarizer can, under certain conditions, be meaningfully reduced to a 2 armed cross-polarizer (Fig.12A). This can be achieved by guiding a partial beam, derived by a polarising transmission of P1, in the optical path S1, by a mirror M onto the polarizer P2 in a way that this polarizer reflects this partial beam. Additionally, the other partial beam, derived from a polarizing reflexion at P1, is guided in the optical path S2 onto P2, optionally by another mirror (M) in a way that this partial beam transmits P2.

The 2 armed cross-polarizer can be used for arbitrary complementary polarization directions. However, there is a significant difference to all 3 armed and 4 armed

cross-polarizers: the partial beams cannot be tapped outside the involved PBSs: the partial beams in S1 and S2 only exist between the two complementary polarization processes. This embodiment can be used for example in two channel display systems with the type MEMS, which are then located on S1 and S2 between P1 and P2 (not shown). Since MEMSs do not modulate the light via a change of polarization, the polarization impurities still contained after one simple polarization, do not interfere with modulation and will be largely removed at superposition. This leads, even with the embodiment of the 2 armed cross-polarizer with MEMSs, to a high channel separation of >5000:1. Crosstalk between the channels is then less than 0.0002. Like in the other embodiments, the two modulated partial beams, superposed in the common ON-beam, can again be split by an external analyzer, e.g. passive polarization glasses.

11. Cross-polarizers with glass prisms

The open 2, 3 and 4 armed cross-polarizers are easily built from single, discrete polarizers. More intricate is the production of the closed form, since the quality and dimensioning of the central crossing line gets important. In DE102004006148 we have introduced prisms, from which the closed form of the cross-polarizer can be built with cartesian palarizers. We have also shown that cartesian polarizers with a layer vector perpendicular to a common ground plane can be replaced by MacNeille type PBSs. Fig.13A shows such a MacNeille type PBS, the polarizing layer of which is positioned between two right prisms. The resulting prism is (Fig.13A) completed with a wire grid polarizer to yield a 3 armed cross-polarizer, with a layer vector of the WGPs chosen such that the WGPs acts complementary to the PBS. As an alternative to the thin-film polarizer P1 there could also be an WGP between T1 and T2 (Figs.13B,C). For some applications, it is useful to add a prism without polarizing function (Figs.13A-C). The closed form of the 4 armed cross-polarizer can be built in multiple ways, e.g with two prisms as shown in Figs.13A-F (an example is Fig.13I) or with four prisms as shown in Fig.13E and/or Fig.13F (as is shown in Fig.13H). Also, a prism as shown in Fig.13A, can be supplemented by a triangular thin-film polarizer without this having a WGP applied (Fig.13G). Those

known to the art or science can deduce many more possibilities. Some of the resulting arrangements may contain a double WGP layer with parallel layer vectors (Figs.13H,I). Alternatively two-sided WGPs can be applied at any layer (as described by e.g. EP1158319, Kameno and Yoshiki, Jasco Corp.; US20030072079 or US20040120041, both by Silverstein et al., Kodak). For the application of the wire grid layers onto the substrates, e.g. glass, several techniques have been described. In addition to the already mentioned WGP of Moxtek we mention alternative methods, e.g from Kodak (e.g. EP1239308, EP1411377). Beside WGP, other cartesian polarizers may also be involved, e.g. from 3M (US6391528, Moshrefzadeh and Thomas).

12. Cross-polarizers concluded with a body

In Fig.14 we show a 4 armed cross-polarizer, which is concluded by a body. This makes it possible to fill gases or fluids in the body, resulting either with a desirable change of refraction properties or, when inert gases are used as filling material, with a reduction of undesired corrosion effects of the wires (e.g. Kane and Kus, US20030117708, Philips). Fig.14A shows the open, Fig.14B the closed form each contained in a body. In the north quadrant a projection optic may be integrated. This may help to accomplish a very compact architecture.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

Fig.1 shows schematically a comparison of a simple and a complex polarizer.
Fig.2 shows schematically the principle of polarizing beam splitters.
Fig.3 shows schematically structural characteristics of the cross-polarizer.
Fig.4 shows schematically functional characteristics of the cross-polarizer.
Fig.5 shows schematically a first and second embodiment of the cross-polarizer.
Fig.6 shows schematically the polarization contrast in the cross-polarizer.
Fig.7 shows schematically a third and forth embodiment of the cross-polarizer.
Fig.8 shows schematically a fifth and sixth embodiment of the cross-polarizer (with spatial light modulators).

Fig.9 shows schematically optional foldings in the light path of the cross-polarizer.
Fig.10 shows schematically a seventh embodiment of the cross-polarizer (made of 4 MacNeille-PBSs).
Fig.11 shows schematically a eighth embodiment of the cross-polarizer (with MEMSs).
Fig.12 shows schematically a nineth embodiment of the cross-polarizer.
Fig.13 shows schematically cross-polarizers with glass prisms.
Fig.14 shows schematically cross-polarizers within compact bodies.

DETAILED DESCRIPTION OF THE FIGURES

Fig.1 compares a simple and a complex polarizer in 2-channel display systems with polarization sensitive reflective spatial light modulators (RLM). Fig.1A shows a design with a single PBS. Incident unpolarized light (IN) is split by the polarizer P1 in two linearly polarized subbeams. „S"-polarized light (dotted line) is directed to RLM1 by polarizing reflexion. „P"-polarized light (solid line) is directed to RLM2 by polarizing transmission. Light beams incident on the RLM at dark pixels (OFF) are reflected without a change of their polarization back to the axis of incidence. Light beams incident on the RLM at bright pixels are reflected after a rotation of their plane of polarization („S"-polarized light is rotated to „P"-polarized light and vice versa), and as a consequence these reflected beams are superposed into a common ON-axis. Fig.1B shows a complex polarizer with four identical MacNeille type polarizers P1 to P4. Unpolarized incident light (IN) is split by P1 into two polarized subbeams. The reflected subbeam from P1 („S"-polarization, dotted line) is also reflected at P3 and is incident on RLM1. The transmitted subbeam of P1 („P"-polarization, solid line) also transmits P2 and is incident on RLM2. Beams incident on RLM at dark pixels remain unchanged in their polarization and are so reflected back to the axis of incidence (OFF). Light beams incident on RLM at bright pixels are rotated in their plane of polarization. They are superposed into a common ON-axis (incident light that transmitted P1 and P2 is now reflected at P2 and P4; incident light that was reflected at P1 and P3 now transmits P3 an P4). Additional clean-up (CP) polarizers are placed between P1/P3 and P2/P4. These clean-up reduce polarization impurities in the

reflected light beams, they make no contribution to the light path.

Fig.2 shows the working principle of polarizing beam splitters and a definition of layer vector V and normal vector N. Thin-film polarizers (e.g. MacNeille-PBS, P1 in Fig.2A) polarize an unpolarized beam into tow linearly polarized subbeams. The planes of polarization E2 and E3 are coupled in such a way to the plane of incidence (POI) that the subbeam derived from a polarizing transmission along the optical axis A1 has a POP parallel to POI („P"-polarization) and the subbeam created by a polarizing reflexion along the optical axis A2 has a POP perpendicular to the POI. A1 is perpendicular to A2 and each axis has an angle of 45 degree with the normal vector N1 (Brewster principle). The layer vector V1, perpendicular to POI, and A2 define the POP E3 of the reflected subbeam; the layer vector V1 and A1 define a plane E1 perpendicular to the POP E2 of the transmitted subbeam. Using cartesian polarizers (e.g. wire grid polarizers WGP, P1 in Fig. 2B), V1 does not depend on POI (accordingly, in polarizers using the brewster principle V1 is always perpendicular to the POI). V1 corresponds to the WGP grid structure and together with A2 defines the POP E3 of the reflected subbeam; V1 and A1 define a plane E1 perpendicular to the POP E2 of the transmitted subbeam. Each POP of the two subbeams can (in contrast to brewster polarizers) have an angle with POI of P1 different from 0 or 90 deg.

Fig.3 shows structural characteristics of the cross-polarizer: three polarizers P1, P2, P3 with the layer vectors V1, V2, V3 and the normal vectors N1, N2, N3 normal to the respective polarizing layer are arranged along two optical axes A1, A2 in a way that said layer vectors and said axes define four planes E1, E2, E3, E4 (V1 and A1 define E1, V2 and A1 define E2, V1 and A2 define E3, V3 and A2 define E4) with E1 perpendicular to E2 and E3 perpendicular E4. The alignment of the optical axis A1 differs from the alignment of both N1 and N2; the alignment of the optical axis A2 differs from the alignment of both N1 and N3. The cutting angle of N1 and A1 equals that of N1 and A2. This three-arm cross-polarizer can be extended to a four-arm cross-polarizer using a fourth polarizer P4 with a layer vector V4 and a normal vector N4 along two further optical axes A3 and A4 resulting in four three-arm cross-

polarizers (P1,P2,P3), (P4,P2,P3), (P2,P1,P4), (P3,P4,P1).

Fig.4 shows functional characteristics of the cross-polarizer: the reciprocal coupling of a polarizing transmission with a polarizing reflexion at two mutually complementary polarizing beam splitters. We call P1 mutually complementary to P2 if they are aligned along an optical axis A1 such that the structural characteristics explained in Fig.3 are provided, E1 being perpendicular to E2. In this case a linearly polarized light beam along axis A1, which transmits P1, is reflected at P2, and a linearly polarized light beam, which transmits P2, is reflected at P1. We call this coupling of a polarizing transmission at one polarizer and a polarizing reflexion at the complementary polarizer to the reverse processes reciprocal coupling of polarizers.

Fig.5 shows a three armed cross-polarizer in a first embodiment of our invention. Three polarizing layers P1, P2, P3 are arranged each perpendicular to a common ground plane parallel to the plane of incidence POI. The layer vectors of the polarizing layers correspond to the wire grid axes and are aligned such, that the structural and functional characteristics outlined in Figs. 3 and 4 are given. We show the split of an unpolarized incident light beam into two linear polarized subbeams of different polarization. The subbeam transmitting P1 is reflected at P2 (the arrow seen at P2 corresponds to the projection of the polarization vector of this beam along the optical axis into the polarization layer P2). The subbeam reflected at P1 transmits P3 (the arrow seen at P3 is the projection of the polarization vector of this beam along the optical axis into the polarization layer P3). After each subbeam is subjected to a polarizing transmission and a polarizing reflexion they are complementarily linearly polarized (which means that their planes of polarization POP are perpendicular if they are defined by a x-y-z-reference system given by the direction of the beam z, the vector x complanar to the POI and perpendicular to z and the vector y perpendicular to POI and perpendicular to z). Fig.5B shows in a second embodiment the layer vector P1 being perpendicular to the POI and the layer vectors of P2 and P3 being parallel to the POI. In this setting P2 and P3 are replaced by a single polarization layer.

Fig. 6 shows how the equally high polarization contrast of 5000:1 in both channels of the cross-polarizer originates when wire grid polarizers WGPs are used (data of WGP beam splitters taken from Kahn: Doing it with stripes, Private Report on Projection Displays, V7, NO.10, 2001, www.profluxpolarizer.com). Polarization layer P1 with a layer vector perpendicular to POI (and, correspondingly perpendicular to the drawing plane) is shown as dotted line. The polarization layers P2 and P3 which are complementary to P1 (thus their layer vectors are in the drawing plane) are shown as solid line. „P"-polarized light (solid thin line) with a polarization vector in the drawing plane maximally transmits P1 (0.885) and is maximally reflected by P2 (0.880, Fig.6A). The complementary „S"-polarized light (dotted thin line) in contrast minimally transmits P1 (0.003) and is minimally reflected by P2 (0.050, Fig.6B). We can calculate a polarisation contrast: an incident unpolarized light beam (combining Fig.6A and 6B) contains after transmitting P1 and reflexion at P2 „P"-polarized light (0,885x0,880) and „S"-polarized light (0,003x0,050) in a P/S ratio of 5000:1 (Fig.6E). Figs.6C and 6D show the complementary situation for the second subbeam. Here, „S"-polarized light maximally transmits P3 and is maximally reflected by P1 (Fig.6D), while the complementary „P"-polarized light minimally transmits P3 and is minimally reflected by P1 (Fig.6C), resulting in a S/P ratio of again 5000:1.

Fig.7 shows a four armed cross-polarizer in a third and fourth embodiment of our invention in a planar arrangement. Adding a fourth polarization layer (P4) we can enhance the three armed cross-polarizer from Fig.5 to a four armed cross. In this exemplary arrangement the polarization layers are perpendicular to each other and perpendicular to a common plane parallel to POI. This cross-polarizer includes several cross-polarizer functions. A first light path (solid line) couples P1 to the two polarizers P2 and P3, which are complementary to P1. A second light path (dotted line) couples P3 polarizers P1 and P4, which are complementary to P3. The layer vectors in Fig.7A (open form) are not aligned specially to the POI. Thus the two light paths (incident light on P1 and P3) result in differently polarized light in both the west-quadrant and east-quadrant. In Fig.7B (closed form) all four polarization layers

meet in one axis normal to the common ground plane. Using layer vectors parallel and perpendicular to the ground plane the two light paths (incident light on P1 an P3) result in equally polarized light in both the west quadrant (entire left side shown as „P"-polarized light) and the east quadrant (entire right side shown as „S"-polarized light).

Fig.8 shows a four armed cross-polarizer in a fifth and sixth embodiment of our invention with 2-channel image modulators. Open form (Fig.8A) and closed form (Fig. 8B) are directly combined with polarization rotating reflective spatial light modulators RLM. In the open form a cross-polarizer (P1,P2,P3) is used to direct incident light towards the two RLMs (IN, „P"-polarized light to RLM1 and „S"-polarized light to RLM2). Light beams incident on the RLM at dark pixels are not modulated, keep their polarization and thus are reflected back to the axis of incidence (OFF). Light beams incident on the RLM at bright pixels are rotated in their plane of polarization (ON); they are superposed in the left side of north quadrant by a second cross-polarizer (P4,P2,P3). The closed form (Fig.8B) makes ist possible to send light both to P1 and P3 using the entire south quadrant. According to Fig.7B, this results for both input cross-polarizers (P1,P2,P3) and (P3,P1,P4) in „P"-polarized light in the entire east quadrant and "S"-polarized light in the entire west quadrant. Two further cross-polarizers (P2,P1,P4) and (P4,P3,P2) are used for superposition. Alltogether, for input into the RLMs and the output of the RLM-ON- and RLM-OFF-light four overlapping cross-polarizers are used. The closed form uses less than 25% of the area needed for the open form.

Fig.9 shows schematically optional foldings in the light path of the cross-polarizer. The principle of reciprocal coupling of two mutually complementary cross-polarizers is shown using a light path S1 with two additional mirrors M. The layer vector V1 of polarizer P1 (we show a MacNeille type-PBS) and the optical axis of S1 in P1 define the plane E1. The layer vector V2 of polarizer P2 (we show a cartesian polarizer) and the optical axis of S1 in P2 define the plane E2. The mirror plane E1* (derived from E1 by successive foldings of E1 at reflexion planes M along S1) is perpendicular to E2. In contrast to the figures above the polarization layers of P1 an P2 are not positioned perpendicular on a common ground plane. N1 is the normal

vector of polarizing layer P1 and N2 the normal vector of polarizing layer P2.

Fig.10 shows in a seventh embodiment of our invention a folded cross-polarizer using four MacNeille-type polarizers P1, P2, P3, P4 and two mirror planes (M; shown are total internal reflexion prisms TIR) combined with polarization rotating reflective RLM1 and RLM2. The IN-beam and the OFF-beam use a cross-polarizer (P1,P3,P2) with additional means of reflexion in each light path. For the superposition of the ON-beams we use a second cross-polarizer (P4,P3,P2) without additional reflexion. This embodiment corresponds to the open form of the four armed cross-polarizer.

Fig.11 shows in a eighth embodiment of our invention, a four armed cross-polarizer in a closed form using reflective RLMs of the DMD-type. These DMDs modulate the incident light (IN) not by rotating the polarization state, but by directing ON- and OFF- light towards different directions. DMD1 and DMD2 show identical topology (are the same stereoisomer type). They reflect light at bright pixels normal the DMD surface. As there is no modulation dependent change of modulation, this ON-light of both DMDs is superposed and reflected back to the quadrant of incidence. Input POI and output POI have an intersection angle adjusted to the mirror deflection angle of the DMD. Light reflected from dark pixels (OFF) is directed towards a light dump (not shown).

Fig.12 shows a two armed form of the cross-polarizer (nineth embodiment of our invention). The three armed cross-polarizer of Fig.12A can be converted to a two armed cross-polarizer by implementation of additional mirrors (M) (Fig.12B). Both subbeams created at P1 („P"-polarized subbeam in ligth path S1 by polarizing transmission of the input beam at P1 and „S"-polarized subbeam in light path S2 by polarizing reflexion of the input beam at P1) are directed toward a second polarizer P2 complementary to P1 in a way, that the „S"-polarized subbeam transmits P2 and the „P"-polarized subbeam is reflected at P2. As both subbeams in S1 and S2 are separated only between the two polarizers, this embodiment can be meaningfully used in 2-channel display systems with spatial light modulators e.g. of the MEMS

type which are placed in S1 and S2 between P1 and P2.

Fig.13 shows cross-polarizers with glass prisms. Fig 13A shows a cross-polarizer made of a right triangular prism, which comprises two right subprisms T1 and T2. Between T1 and T2 there is a polarizing layer P1 of the Brewster type. The continuous surface of the prism which consists of two surfaces of the two subprisms carries a cartesian polarisation layer P2/P3 with a layer vector V2 parallel to the common ground plane. A third glass prism may be added to the arrangement (see Fig.13A-C). In Fig.13B P1 is a cartesian polarization layer. Fig.13C corresponds to Fig.13B with swapped layer vectors. Fig.13D-F show prism arrangements with cartesian layers with which cross-polarizers (three or four armed) can be built. Two prisms of Fig.13D-F suffice to build a four armed cross-polarizer. Four prisms of Fig.13E-F result in a four armed cross-polarizer having double layers (Fig.13H). In Fig.13F the polarisation layers are mounted to a lateral surface of subprisms T1a and T1b. In Fig.13G a four armed cross-polarizer is constructed by adding a triangular MacNeille type polarizer to the three armed cross-polarizer shown in Fig.13A. Fig.13I shows exemplarily a four armed cross-polarizer in which the polarizing layers are not orthogonal to each other.

Fig.14 shows cross-polarizers within a closed body. Fig.14A shows the open form, Fig.14B the closed form of the four armed cross-polarizer each contained in a single body. Openings can be used to directly mount RLMs (Fig.14B). It is also possible to integrate optical elements as projection lenses L to the body of the cross-polarizer.

It will be appreciated that whilst this invention is described by way of detailed embodiments, these realizations serve as illustrations of the invention but not as a limitation of the invention; numerous variations in form and detail can be deduced by those skilled in the art or science to which this invention pertains without leaving the scope of the invention as defined by the following claims: